Available Capacity based AGC Signal Distribution Strategy with Energy Storage System

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***Abstract*—With the increasing penetration of wind power integration, more frequency regulation resources are needed to maintain the power system frequency stability. A distribution strategy of automatic generation control (AGC) signal is proposed to allocate the area control error (ACE) among different generators and energy storage system (ESS). The available AGC capacities (AAC) of generators are evaluated by considering the remained regulation capacity and ramp rate. The AAC of ESS is evaluated with a dynamic power output bound based on rated power and real-time SOC. An AGC signal distribution strategy based on AAC is proposed to decide the change of power references for generators and ESS to fully utilize the long supporting duration of generators and high response rate of ESS. The effectiveness of proposed approach is verified through case studies based on a modified IEEE 30-bus test system.**

***Index Terms*— Area control error (ACE); automatic generation control (AGC); available AGC capacities (AAC); energy storage system (ESS).**

I. Introduction

The volatility and uncertainty of wind power introduce new challenges to power system frequency regulation and control. The dependence of wind power generation on wind speed results in more disturbance on system power balance. Meanwhile, most of wind turbines works in maximum power point tracking (MPPT) mode and are decoupled with system frequency dynamic [1, 2]. Thus the total online regulation resources are also reduced when some conventional generators are replaced by wind power. As a result, frequency stability has become one of the major bottlenecks in increasing wind power penetration [3].

A number of researches have been conducted to improve the frequency regulation performance of power system with high penetration of wind power, including the wind power side and the power system side [4, 5]. In the wind power side, different wind farm models for participating in power system inertia support, primary frequency control and automatic generation control (AGC) have been investigated [6, 7]. However, most of frequency support from wind farms are based on the loss of wind power capture or power conversion efficiency. There are also some approaches focus on enhancing the regulation control in power system side. An intelligent agent based AGC design is presented in [8] to handle wind power variation with structure flexibility and independence to the power system parameters. The control gain for proportional-integral (PI) controller in AGC is tuned by a dynamic gain-tuning control method in [5] to obtain a proper AGC signal, which would be distributed to different generators. Normally, the AGC signal distribution is realized by a per-MW basis in most of Independent System operators (ISOs), without regard for speed of response [9]. Whereas, some generators with larger participation capacities may have slower response rate. The AGC response may not satisfy the AGC signal promptly due to the low ramp rates of some generators.

Besides the conventional frequency regulation, some new resources are also introduced to increase the capability of power system to handle wind power integration. A demand side response strategy based on price is proposed in [10] to provide reserves for wind power integration. Distributed generations (DGs) can also provide AGC service to reduce the area control error (ACE) [11]. Energy storage system (ESS) has been regarded as one of the most potential resources to provide high-efficiency frequency regulation support due to its high response rate [12]. However, the high cost and limited energy capacity of ESS require a proper control strategy for ESS to participate in frequency regulation. There are mainly two different kinds of approaches to dispatch ESS in AGC. In first kind of approach, ESS is set in the highest priority group, which means ESS always undertake the AGC signal with its maximum capability to make full use of its high ramp rate [13]. This kind of approach would easily result in ESS reaching its upper or lower energy limit. A secondary frequency disturbance occurs when the power support of ESS disappear suddenly. Thus a proper state of charge (SOC) management is necessary. A dynamic available AGC based approach is presented in [9] to decide AGC signal for ESS considering the SOC of ESS. In the other kind of approach, ESS is set to only response to high frequency AGC signal due to its limited energy capacity. But it cannot provide full power support immediately when it is needed. In conclusion, a proper SOC management of ESS and a coordination control

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between generators and ESS are crucial to make full use of ESS in frequency regulation.

In order to coordinate generators with different ramp rates and ESS with limited energy capacity, an available AGC capacity (AAC) based AGC signal distribution strategy is proposed in this paper to decide the AGC signal for different generators and ESS. The AAC of generator is evaluated by considering the remained regulation capacity and ramp rate. The AAC of ESS is described with a dynamic power output bound based on the rated power and real-time SOC. The AGC signal is distributed by fully utilizing the long supporting duration of generator and high response rate of ESS.

II. Frequency Regulation Model with Energy Storage System

A. Power System Frequency Regulation Model

According to the response time scale, power system frequency regulation can be divided into three stages, as shown in Fig. 1. The first one is the system inertia, which decides the rate of change of frequency (RoCoF) caused by a certain power unbalance, such as generation trip, load and wind power variation, and leads to a frequency deviation. After that, the load frequency response and generator governor system will be implemented to change the load and power output of generator according to the frequency deviation, which is called the primary frequency regulation. The power references of generators are adjusted according to ACE to recover system frequency to nominal value, as called secondary frequency regulation or AGC [14].

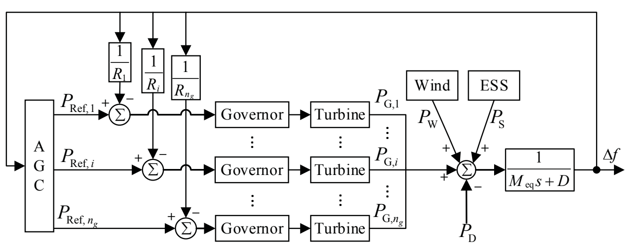

Fig. 1. Frequency regulation with wind power and ESS integration.

In a power system with wind power and ESS integration, the frequency deviation Δf can be modeled as

$$\Delta f = \frac{1}{M_{\mathrm{eq}} s + D}\left(\sum_{i=1}^{n_g} P_{\mathrm{G},i} + P_{\mathrm{W}} + P_{\mathrm{S}} - P_{\mathrm{D}}\right) \tag{1}$$

where, M_{eq} is the equivalent inertia of system consist, D is the load regulation coefficient, $P_{\mathrm{G},i}$ is the power output of generator i, n_{g} is the number of generators, P_{W} is the wind power output, P_{D} is the power demand, P_{S} is the power output of ESS. A positive value of P_{S} means discharge, vice versa.

Without considering the dynamic characteristic of governor, the primary control of generator can be described as

$$P_{G,i} = P_{Ref,i} - \frac{1}{R_i}\cdot\Delta f \tag{2}$$

where, $P_{Ref,i}$ is the power reference of generator i, R_i is the droop coefficient of generator i.

The typical AGC model is illustrated in Fig. 2. The ACE is calculated with frequency bias β and the needed regulate power P_{REG} can be obtained after a PI controller and divided to the power reference adjustment of each generator with AGC signal distribution algorithm.

$$\beta = \sum_{i=1}^{n_g}\frac{1}{R_i} + D \tag{3}$$

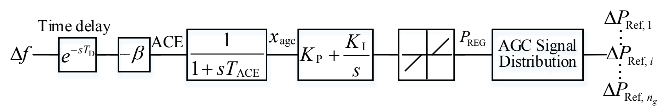

Fig. 2. Typical AGC model.

The new power reference of generator can be calculated as

$$P_{\mathrm{Ref},i} = P_{\mathrm{Ref0},i} + \Delta P_{\mathrm{Ref},i} \tag{4}$$

where, $P_{\mathrm{Ref0},i}$ is the original power reference of generator i.

In order to recover system frequency to the nominal value, the sum of $\Delta P_{\mathrm{Ref},i}$ should be equal to P_{REG} .

$$\sum_{i=1}^{n_g}\Delta P_{\mathrm{Ref},i} = P_{\mathrm{REG}} \tag{5}$$

B. ESS Model for Frequency Regulation

Due to the high response rate and limited energy capacity of ESS, frequency regulation has been regarded as a potential application of ESS in power system operation. A typical model of ESS participating in frequency regulation can be described as

$$P_{\mathrm{S}} = P_{\mathrm{Ref,S}} - \frac{1}{R_{\mathrm{S}}}\cdot\Delta f \tag{6}$$

where, P_{S} and $P_{\mathrm{Ref,S}}$ are the power output and power reference of ESS, R_{S} is the virtual droop coefficient of ESS.

With the participation of ESS, (5) can be modified as

$$P_{\mathrm{Ref,S}} + \sum_{i=1}^{n_g}\Delta P_{\mathrm{Ref},i} = P_{\mathrm{REG}} \tag{7}$$

Due to the limited energy capacity of ESS, it is crucial to monitor the energy state of ESS, i.e., state of charge (SOC).

$$SOC = \begin{cases} SOC_0 - \dfrac{\lambda_{\mathrm{S}} P_{\mathrm{S}}\Delta t}{C_{\mathrm{S}}}, & \text{if } P_{\mathrm{S}}<0 \\ SOC_0 - \dfrac{P_{\mathrm{S}}\Delta t}{\lambda_{\mathrm{S}} C_{\mathrm{S}}}, & \text{if } P_{\mathrm{S}}>0 \end{cases} \tag{8}$$

where, λ_S is the efficiency coefficient of ESS, C_S is the rated capacity of ESS, SOC_0 is the initial SOC, Δt is the time interval. In this paper, $\lambda_S = 0.9$.

III. AGC Signal Distribution Strategy with ESS

A. Available AGC Capacity of Generators

For ensuring the frequency stability of power system, (5) or (7) should be satisfied to compensate the power unbalance. However, the available capacities and response rates of generators may be not sufficient for some large power unbalance, as well as the rated power and energy capacity of

ESS. Thus a proper evaluation of the AAC for generators and ESS is essential for the AGC signal distribution.

The AAC of generator can be evaluated by considering the remained regulation capacity and the ramp rate as follow.

$$AAC_i = \begin{cases} \min\{dP_{G,i}T_{agc}, P_{Gmax,i} - P_{G,i}\}, & \text{Reg. up} \\ \max\{-dP_{G,i}T_{agc}, P_{Gmin,i} - P_{G,i}\}, & \text{Reg. down} \end{cases} \quad (9)$$

where, $dP_{G,i}$ is the ramp rate of generator i, $P_{Gmax,i}$ and $P_{Gmin,i}$ are the upper bound and lower bound of generator i, T_{agc} is the cycle time of AGC, which is about 4~6 seconds. In this paper, T_{agc} is set as 4 seconds.

B. Available AGC Capacity of ESS Based on SOC

The available AGC capacity of ESS can be described as the power output bound of ESS, $P_{S,max}$ and $P_{S,min}$. They are not only restricted by the rated power capacity of ESS, but also depend on the real-time SOC, i.e., the energy remained in ESS. The SOC of ESS should be kept in the allowable range to ensure the lifetime and operation security of ESS.

$$-P_{S,rated} \le P_S \le P_{S,rated} \quad (10)$$

$$SOC_{min} \le SOC \le SOC_{max} \quad (11)$$

where, SOC_{min} and SOC_{max} are the lower bound and upper bound of SOC. In this paper, SOC_{min} = 10% and SOC_{max} = 90%.

Without a proper management of SOC, the positive or negative power support from ESS would disappear suddenly when SOC of ESS reaches its lower bound or upper bound, which will result in additional frequency disturbance. Thus a dynamic power output bound evaluation of ESS is proposed to regulate the SOC and corresponding power output of ESS, as shown in Fig. 3.

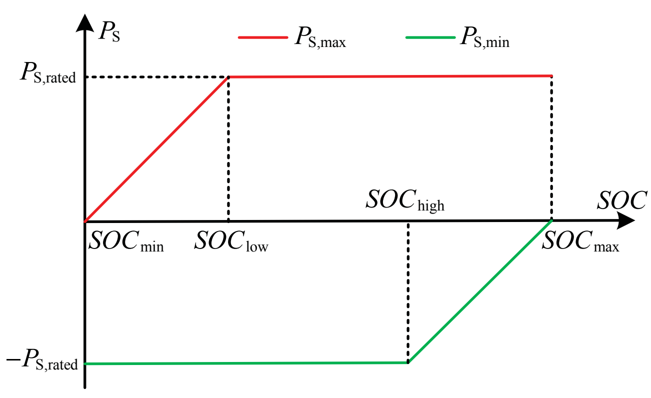

Fig. 3. Dynamic maximum power output of ESS based on SOC.

If SOC is lower than a threshold level SOC_{low} , the maximum power output of ESS for discharge $P_{S,max}$ will decrease according to the value of SOC and reach to zero when SOC down to SOC_{min}. Similarly, the minimum power output of ESS for charge $P_{S,min}$ (negative) will increase according to the SOC that is larger than SOC_{high} and reach to zero when SOC up to SOC_{max}.

Then the dynamic power output bound of ESS can be updated as

$$P_{S,min} \le P_S \le P_{S,max} \quad (12)$$

C. AGC Signal Distribution with ESS

Without considering ESS, the AGC signal distribution strategy for generators based on AAC can be realized as

$$\Delta P_{Ref,i} = \begin{cases} \dfrac{AAC_i}{\sum AAC_i} \cdot P_{REG}, & \text{if } \sum AAC_i > P_{REG} \\ AAC_i, & \text{if } \sum AAC_i \le P_{REG} \end{cases} \quad (13)$$

Considering the fast response rate and limited energy capacity of ESS, as well as the long support duration and slow ramp rate of generators, an AAC based AGC signal distribution strategy with ESS participation is proposed to utilize the respective advantages of generators and ESS, as shown in Fig. 4.

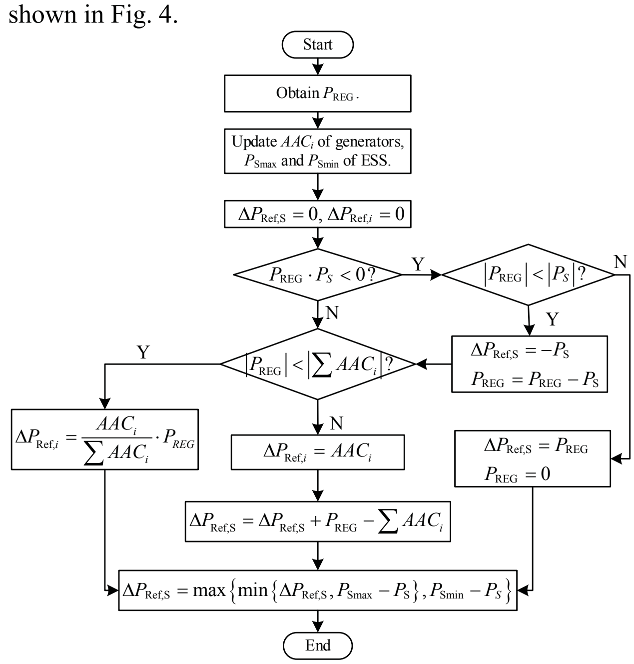

Fig. 4. AGC signal distribution strategy for generators and ESS.

Several principles are presented to coordinate the AGC signal distribution between generators and ESS as follow.

(1) When the output power of ESS is zero, if the total AAC of generators is sufficient for P_{REG} , keep the capability of ESS for next time, if not, ESS should take the overload part as possible.

(2) If ESS is in charge state ($P_S < 0$) and P_{REG} is positive, it is called the state of ESS is opposite with P_{REG} , as well as $P_S > 0$ and P_{REG} is negative. In this situation, the power output of ESS should be adjusted to zero before dispatching generators.

(3) If the state of ESS is the same with P_{REG} and AAC of generators are sufficient for P_{REG} , try to transfer the load from ESS to generators, with the purpose of reserving the high-rate capacity of ESS and avoiding out-of-limit of SOC.

IV. Case Studies

A. Test System

In order to verify the proposed approach, a modified IEEE 30-bus 6-generator system with 100 MW wind power integration is presented [15]. The technical data of generators is presented in Table I. The wind power generation is shown in Fig. 5. The load is set to be constant during simulation period as 235 MW, G2~G6 are set to be online. The energy storage is set as 3 MW/ 1 MWh.

Two cases are compared to shown the performance enhancement by ESS participation in frequency regulation.

- Case A: without ESS;
- Case B: with ESS, G5 does not participate in regulation.

TABLE I. TECHNICAL DATA OF GENERATORS

Unit	P_G (MW)	P_{Gmax} (MW)	P_{Gmin} (MW)	*Ramp Rate* (MW/min)
G1	0	200	50	6
G2	70	80	20	2
G3	40	50	15	1.5
G4	29	35	10	1.5
G5	20	30	10	1
G6	35	40	12	2

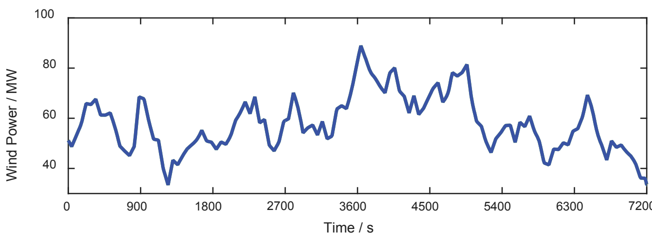

Fig. 5. Wind power generation for simulation.

B. Frequency Rgualtion after Sudden Drop of Load

Assume the load has a sudden drop of 5 MW at t = 10 s and wind power keeps constant. A comparison of frequency regulation performance between case A and case B is presented in Fig. 6 and Fig. 7. The maximum frequency deviation of case B is smaller than the one of case A and the frequency deviation of case A also recovers to a small range faster than case B, as shown in Fig. 6. Meanwhile, Fig. 7 illustrates that the response rate of power system to ACE increases with ESS participation in AGC.

As shown in Fig. 8, the power output of ESS declines immediately based on the primary frequency responses to frequency deviation. Then the AGC signal distribution strategy starts to adjust the power reference of ESS to compensate the power unbalance due to the insufficient of generators' ramp rates. After keeping the power support for a while and waiting for generators to adjust their power reference, ESS reduces its power output gradually to reserve the high rate response capability.

C. Frequency Rgualtion with Wind Power Variation

A two-hour simulation is presented to verify the frequency regulation performance of proposed approach with wind power variation. Fig. 9 shows the frequency deviation for case A and case B. The maximum absolute values and standard deviations (STD) of frequency deviation are presented in Table II. It can be found that ESS with a capacity of 3 MW and 1 MWh has better regulation performance than generator G5 with bidirectional regulation capacity of 10MW.

Fig. 10 and Fig. 11 show the AGC signal and AGC response of two cases with wind power variation. The satisfaction ratio is presented to evaluate the AGC response performance, which represents the percentage time when the AGC response satisfy the AGC signal. As shown in Table II, the AGC satisfaction ratio of case B is about 10% high than the one of case A.

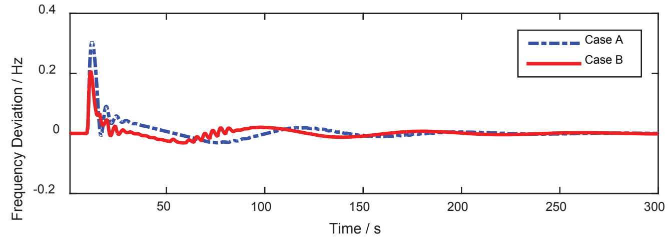

Fig. 6. Frequency deviation after a sudden drop of load.

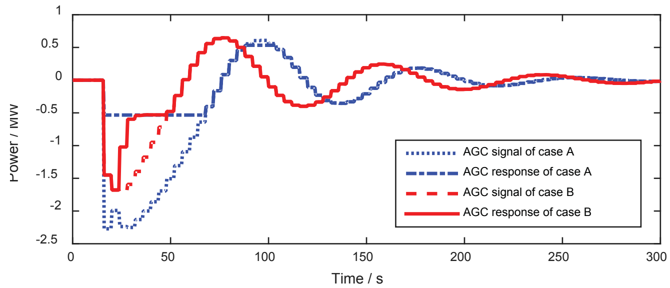

Fig. 7. AGC signal and AGC response after a sudden drop of load.

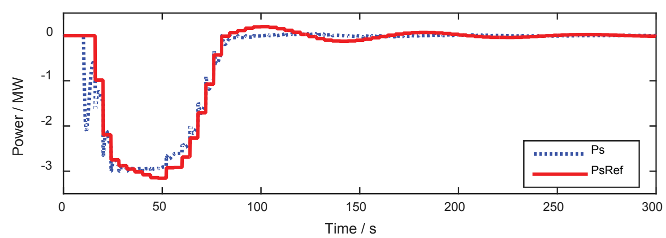

Fig. 8. Power output and power reference of ESS after a sudden drop of load.

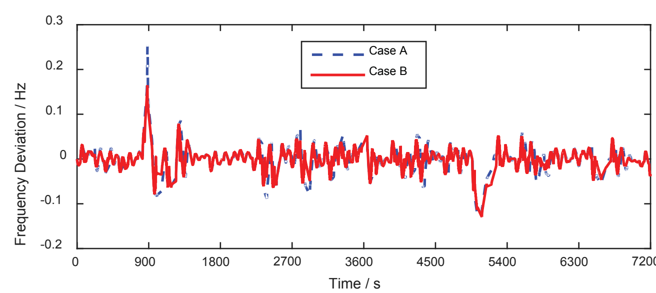

Fig. 9. Frequency deviation with wind power variation

TABLE II. FREQUENCY DEVIATION RESULTS FOR DIFFERENT CASES

Case	*Maximum Frequency Deviation*	*STD of Frequency Deviation*	*AGC Satisfaction Ratio*
A	0.2538 Hz	0.0343 Hz	73.89%
B	0.1653 Hz	0.0278 Hz	84.06%

As shown in Fig. 12, ESS only provides AGC support when the total capability of generators is not sufficient and reduce the power output after temporary support if the generators can satisfy the AGC signal. Fig. 13 and Fig. 14 illustrate the SOC variation of ESS and the corresponding dynamic output power bound of ESS. It can be found that the maximum power output of ESS varies according to the SOC of ESS when SOC is under SOC_{low}. The minimum power output of ESS (maximum charge power) keeps constant due to SOC does not exceed SOC_{high}.

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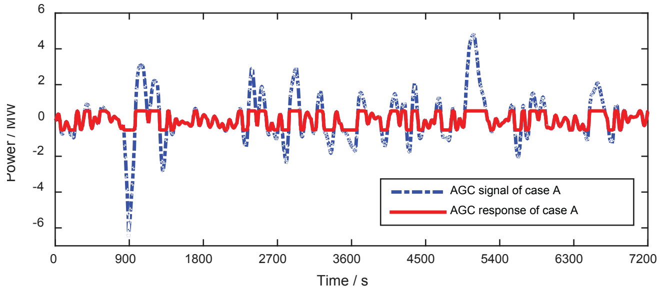

Fig. 10. AGC signal and AGC response of case A with wind power variation.

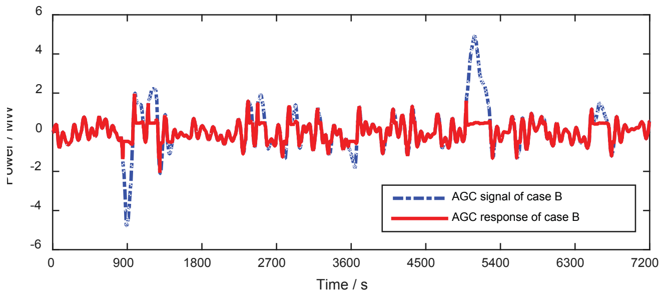

Fig. 11. AGC signal and AGC response of case B with wind power variation.

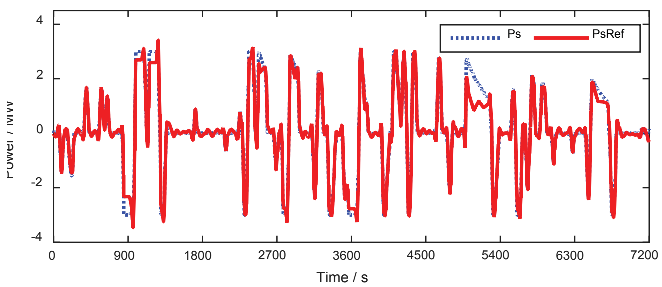

Fig. 12. Power output and power reference of ESS with wind power variation.

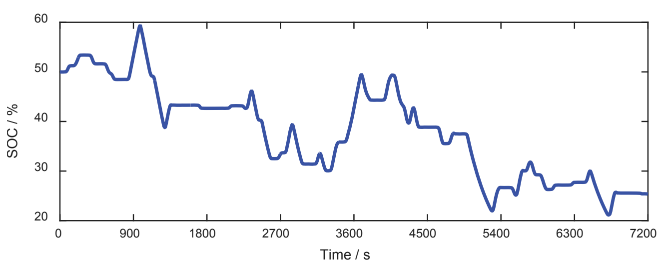

Fig. 13. SOC of ESS with wind power variation

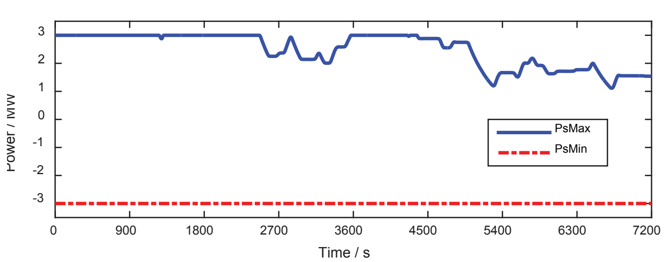

Fig. 14. Maximum and minimum power output of ESS.

V. Conclusion

In this paper, the available AGC capacities of generator and ESS evaluated with AAC and dynamic power output bound can provide accurate information about the capabilities of different generators and ESS. The proposed AGC signal distribution strategy can fully utilize the respective advantages of generators and ESS, while maximizing the available capacity for the following regulation.

The simulation results show that an ESS with capacity of 3MW and 1MWh can provide better frequency regulation performance than a generator with bidirectional regulation capacity of 10MW. With coordination with generators, the system with ESS participation can realize smaller frequency deviation and high AGC response satisfaction.

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